Engineering Performance of Rooftop Gardens through Field Evaluation

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ABSTRACT

Rooftop gardens or green roofs have the potential to reduce urban heat island and storm water runoff. They can also increase membrane durability, provide green space in urban areas, and improve property value. Although green roofs represent an inexpensive adaptation strategy for urban areas, technical information on the benefits and durability, in a Canadian context, is not available. To address these issues, the National Research Council of Canada (NRC), in collaboration with members of the North American roofing industry, initiated a research project in 2000 to provide such information. The main objective of this study was to evaluate the engineering performance of green roofs through field study.

NRC constructed an experimental facility, the Field Roof Facility (FRF), in its Ottawa campus in 2000. This provided an experimental roof area of about 72 m2 (800 ft2). The roof is divided in two equal areas by a 1-m (3-ft) median divider. On one side, a generic green roof was installed and on the other, a conventional roofing assembly with modified bituminous membrane was installed as a reference roof. Both roof sections were instrumented to monitor temperature profile, heat flow, solar reflectance, relative humidity, soil moisture content, and stormwater runoff. This setup allows direct comparison of the performance and benefits of the Green Roof and the Reference Roof.

Observations from the FRF showed that a generic extensive green roof with 150 mm (6 in.) of growing medium could reduce the temperature and the daily temperature fluctuation experienced by the roof membrane significantly in the warmer months. While the exposed roof membrane on the Reference Roof was recorded to reach over 70°C (158°F) in the summer, the membrane underneath the Green Roof reached about 30°C (86°F). In spring and summer, the median daily temperature fluctuation of the membrane was reduced from 42-47°C (76-85°F) on the Reference Roof to 5-7°C (9-11°F) under the Green Roof. The Green Roof also significantly moderated the heat flow through the roofing system and reduced the average daily energy demand for air conditioning due to the heat flow through the roof in the summer by more than 75%. The Green Roof was shown to delay stormwater runoff and reduce peak runoff rate and volume. It retained 245 mm (9.64 in.) out of the 450 mm (17.72 in.) of rain which fell from April to September 2002 – a reduction of 54%.

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Karen Liu, with the Building Envelope and Structure program of the Institute for Research in Construction, National Research Council of Canada, has more than 10 years of research and development experience in polymers and composite materials. Her areas of expertise include: mechanical characterization and failure mechanisms of polymers and composites. Liu's current research interests include environmental effects on the durability of construction materials, chemical analysis of polymeric and asphalt-based roofing membranes, and energy efficiency and environmental benefits of rooftop garden systems.

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INTRODUCTION

Green roofs or rooftop gardens are roofs planted with vegetation. Green roofs are not a new concept and can be traced back to the hanging gardens of Babylon [1]. With advances in roofing materials, innovative research and technical development of roofing components, green roof systems can now be installed successfully under most climatic conditions. Given the limited space available for parks and green space in many North American metropolitan cities, placing the vegetation on otherwise unused building rooftops becomes an attractive building design option.

Green roofs not only add aesthetic appeal to the unused roof space that is available in most urban areas; they also provide many benefits. Green roofs can protect the roofing membrane from exposure to ultraviolet radiation and hail damage. They can reduce energy demand on space conditioning, and hence greenhouse gas emissions, through direct shading of the roof, evapotranspiration, and improved insulation values [2-7]. If widely adopted, green roofs could reduce the urban heat island [8-9] (an elevation of temperature relative to the surrounding rural or natural areas due to the high concentration of heat-absorbing dark surfaces such as rooftops and pavements) which would further lower energy consumption in the urban area. They can also be used as part of the stormwater management strategy in the urban area. Part of the rain is stored in the growing medium temporarily, to be taken up by the plants and returned to the atmosphere through evapotranspiration [2,7,10-11]. Green roofs delay runoff into the sewage system, thus helping to reduce the frequency of combined sewage overflow (CSO) events, which is a significant problem for many major cities in North America [7]. The plants and the growing medium can also remove airborne pollutants picked up by the rain, thus improving the quality of the runoff. In addition, green roofs can improve air quality, provide additional green space in urban areas, and increase property values [12].

Green roofs are found throughout many European countries such as France, Germany, and Switzerland. It has become a multi-million dollar industry in Germany [12], where a significant amount of technical research was carried out on root repelling agents, waterproof membranes, drainage, lightweight growing media, and plants. Green roofs are rapidly gaining popularity across different parts of the world as well. In North America, Portland, Oregon has pioneered an incentive program (Clean Air Incentive and Discount Program) to encourage the installation of green roofs on commercial, industrial, institutional, and residential properties, with the aim of reducing the stormwater runoff problem and relieving the loading on the sewage infrastructure [13]. In Asia, Tokyo, Japan has initiated a new ordinance to install green roofs on new buildings with floor space more than 1000 m2 (10,800 ft2) to mitigate the urban heat island effects [14].

A green roof system requires additional roofing components (*Figure 1*). These components consist of a specialized roof waterproofing membrane, a drainage layer, a filter membrane, a growing medium, and vegetation.

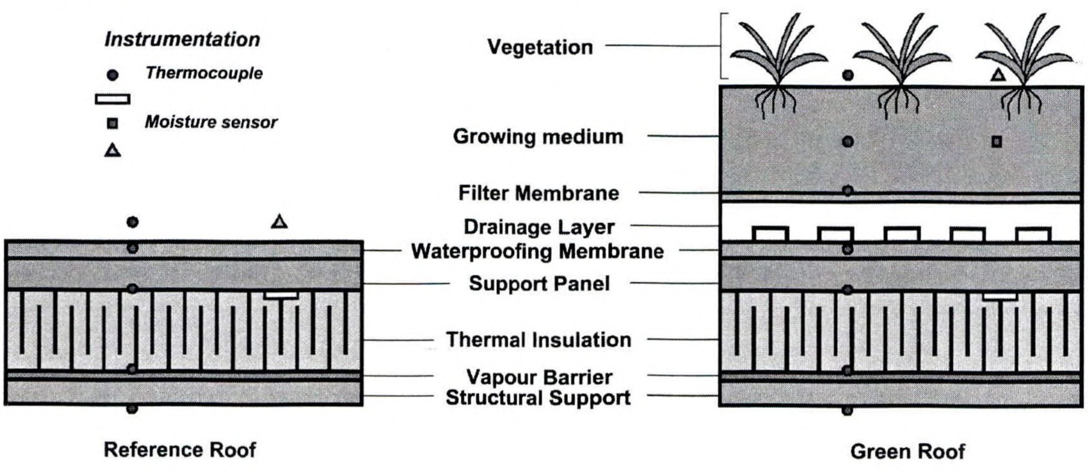

Figure 1: Major components and instrumentation location of the Green Roof and the Reference Roof.

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1. **Waterproofing Membrane:** The most important component of any roofing system is the waterproofing membrane that prevents water penetration into the building. To prevent root damage to the roofing membrane, some manufacturers incorporate a root repellant agent in the formulation of the roof membrane, while others offer a physical root barrier, which can be a layer of PVC, TPO, or high-density polypropylene.

2. **Drainage Layer:** The drainage layer is installed over the waterproofing membrane to remove excess water from the growing medium. This comes in different forms – from a simple layer of gravel to specialized polymer foam panels or highly porous polymeric mat. In some cases, the drainage layer can also be designed to retain some water and serve as a reservoir for irrigating the plants between rainfalls.

3. **Filter Membrane:** The filter membrane is a geotextile filter fabric that is installed on top of the drainage layer. It prevents fine particles in the growing medium from clogging the drainage layer.

4. **Growing Medium:** The growing medium supports plant growth. Its composition and depth depend on the vegetation selected. Water saturated soil can be heavy and the roof structure should be designed to bear the load. Artificial lightweight growing medium can be used to replace regular soil to reduce the weight.

5. **Vegetation:** The plants should be selected for their adaptability to the local climate. Considerations should be given to the more extreme conditions experienced on rooftops, such as exposure to a wide range of temperatures and soil moisture levels, higher winds (erosion of plants and soil), and solar exposure. An irrigation system might be needed, depending on the plants and weather conditions.

The National Research Council of Canada (NRC), in collaboration with members of the North American roofing industry, is leading a research project to study the thermal performance and environmental benefits of green roof technology. The objectives of this project are to identify sensitivities to climate variability and to quantify the benefits of the technology under Canadian climatic conditions. This paper summarizes the results and findings from the first two years of this study.

EXPERIMENTAL STUDY

NRC has constructed the Field Roofing Facility at its Ottawa campus in Canada *(Figure 2)*. It provides an experimental roof area of about 72 m2 (800 ft2) and can represent a low-slope industrial roof with a high roof-to-wall ratio. The roof is divided into two equal areas separated by a median divider. A generic extensive green roof was installed on one side and a modified bituminous roofing assembly was installed as a reference on the other. The Reference Roof represents a conventional roofing system commonly installed in Canada. It consists of a structural deck, a vapor barrier, thermal insulation, support panel, and a 2-ply modified bituminous waterproofing membrane. The cap sheet is covered with light grey colored granules, which are intended to avoid the extreme colors of a reflective white membrane or a dark, built-up roof surface. While the Green Roof has the same basic components up to the membrane level, it incorporates additional elements, such as root repellent in the membrane, a drainage layer, a filter membrane, and a lightweight growing medium (150 mm or 6 in.) to support plant growth. Figure 1 shows the components and configurations of the two roofing systems. In the first year of the study (2001), a wild flower meadow was established in the garden and in the second year (2002),

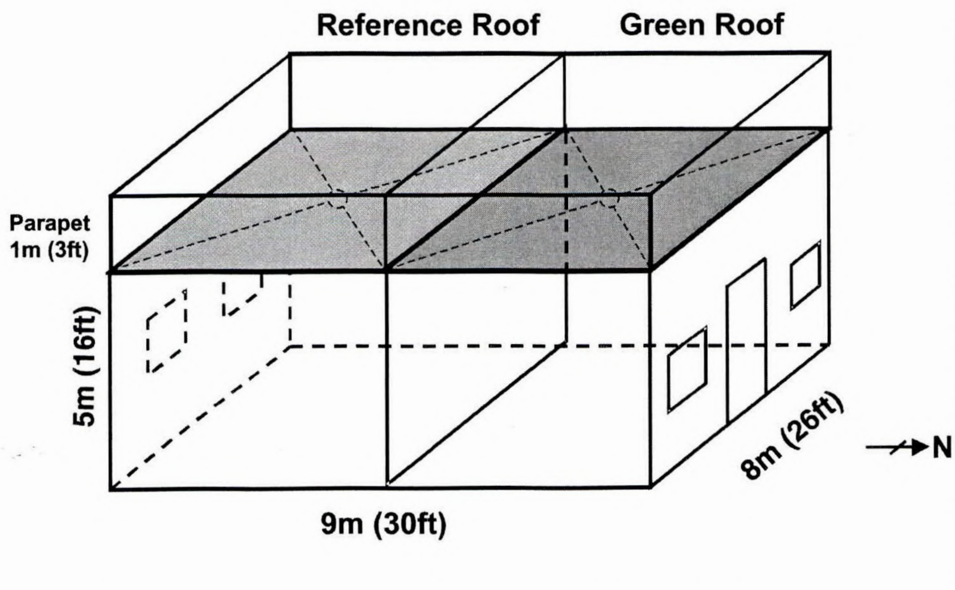

***Figure 2:** Schematics of the Field Roofing Facility (FRF) at the NRC campus in Ottawa. Each roof section is sloped at 2% to a central drain where the runoff is collected and monitored in the building.*

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Figure 3: A wild flower meadow was established on the FRF in the NRC campus in Ottawa (2001).

the garden was planted with sod (Kentucky blue grass). The facility as it appeared in the summer of 2001 and 2002 is shown in *Figures 3 and 4*.

Both the Green Roof and the Reference Roof are instrumented to measure the temperature profile within the roofing system, heat flow across the system, solar reflectance of the roof surface, soil moisture content, microclimate created by the plants, and stormwater runoff (*Figure 1*). The local meteorological data such as temperature, relative humidity, rainfall, and solar radiation are monitored continuously by a weather station located at the median divider on the rooftop and an additional weather station situated approximately 50 m (160 ft) from the site. All sensors are connected to a data acquisition system for monitoring.

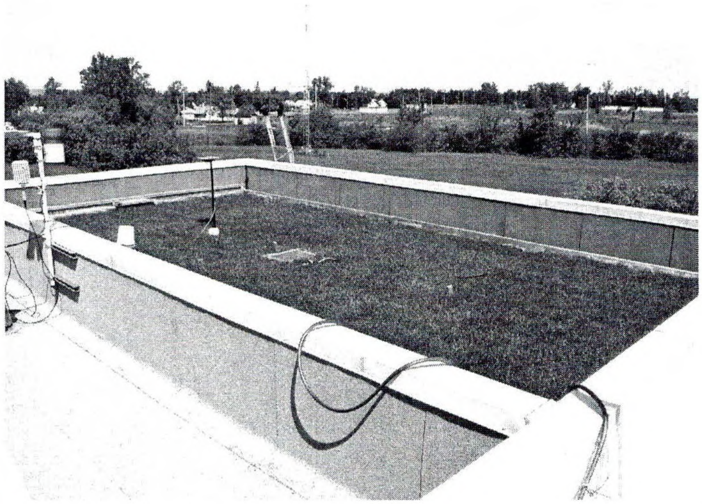

Figure 4: The sod two weeks after installation on the FRF of the NRC campus in Ottawa (2002). Note that the median divider separates the Green Roof (left) and the Reference Roof (right). The weather station is located at the median divider.

RESULTS AND FINDINGS

The Field Roofing Facility has been in operation since November 2000. The data collected from the first two years of operation (November 2000 to September 2002) have been analyzed and are summarized below.

Temperature Profile

An exposed roof membrane absorbs solar radiation during the day and its temperature rises. The extent of the temperature increase depends on the color of the membrane. Light color membranes are cooler because they reflect solar radiation, but dark color membranes are hotter because they absorb much of the solar radiation.

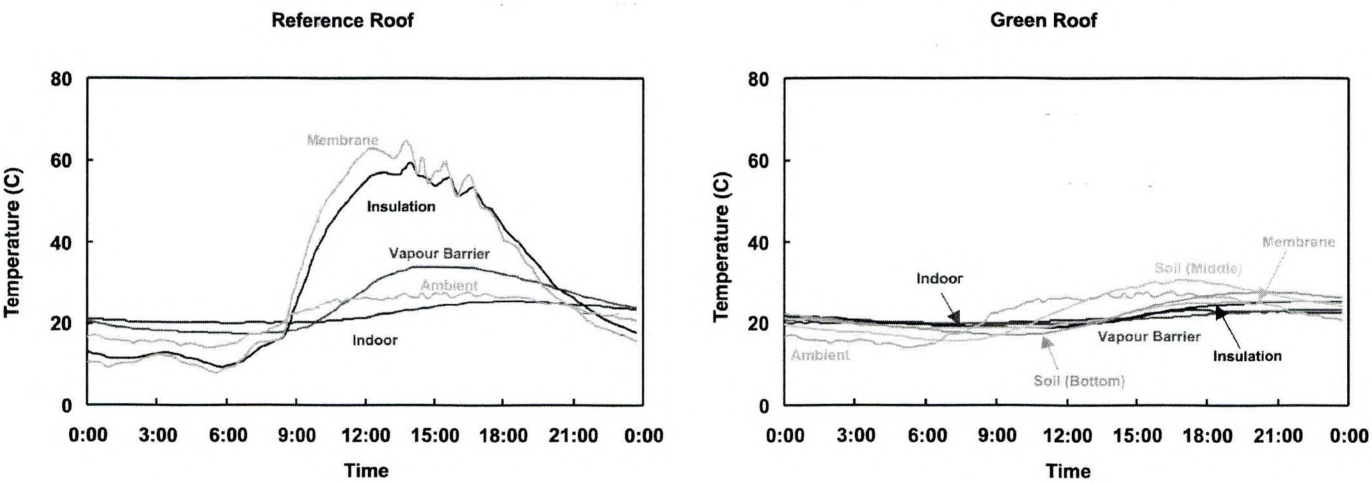

Figure 5: Temperature profile within the roofing systems on a summer day (July 16, 2001), indicating that the Green Roof reduces the temperature fluctuations within the roofing system.

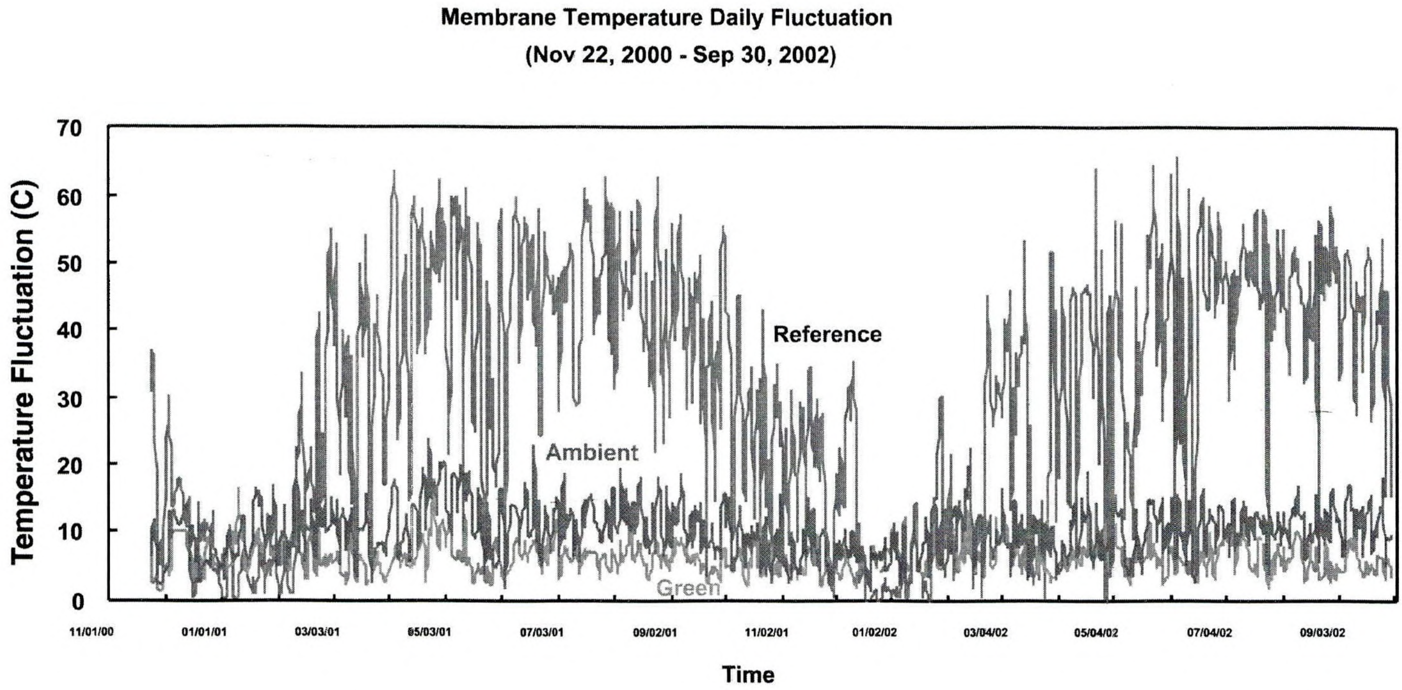

Figure 6: Temperature measurements showed that the Green Roof significantly reduced the daily temperature fluctuations experienced by the roofing membrane.

Results from the FRF show that the roof membrane on the Reference Roof experienced much higher temperatures than that on the Green Roof. *Figure 5* shows the temperature profile within the roofing systems on a summer day. The membrane on the Reference Roof absorbed the solar radiation and reached close to 70°C (158°F) in the afternoon. However, the membrane on the Green Roof remained around 25°C (77°F).

Table 1 compares the number of days out of the observation period (a total of 660 days) when the maximum roof membrane temperature exceeded various levels. For example, there are 219 days out of the 660 days (i.e., 33% of the days) observed that the membrane on the Reference Roof reached a temperature above 50°C (122°F). However, the roof membrane reached above 60°C (440°F) only on 89 of the 219 days – 13% of the days observed during this period (i.e., 89 days out of 660 days). While the ambient temperature exceeded 30°C (86°F) for 10% of the days during the 22-month observation period, the membrane temperature of the Reference Roof went above 30°C (86°F) over half of the time, compared to only 3% for the Green Roof. In fact, the Reference Roof membrane reached over 50°C (122°F) about one third of the days during the observation period and reached over 70°C (158°F) in the extreme conditions. Note that the color of the membrane was light grey; the temperature of a dark color membrane would be expected to be even higher.

Temperature Greater Than:	Reference Roof		Green Roof		Ambient	
	# of Days	% of Days	# of Days	% of Days	# of Days	% of Days
30°C (86°F)	342	52	18	3	63	10
40°C (104°F)	291	44	0	0	0	0
50°C (122°F)	219	33	0	0	0	0
60°C (140°F)	89	13	0	0	0	0
70°C (158°F)	2	0.3	0	0	0	0

Table 1: Statistics on the daily maximum temperature of the roof membranes on FRF during the observation period (660 days in total).

Heat exposure can accelerate aging in bituminous material, thus reducing its durability. In the roofing industry, heat aging at 70°C (158°F) is commonly used as an accelerated aging test for these materials (e.g., ASTM D5869, "Standard Practice for Dark Oven Heat Exposure of Bituminous Materials"). Ultraviolet radiation can change the chemical composition and degrade the mechanical properties of the bituminous materials. Although long-term durability data is not yet available from the study, the growing medium and the vegetation of the green roof can prevent the UV radiation from attacking the roofing membrane and minimize aging of the membrane from heat exposure, which might extend the life of the membrane.

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Temperature Fluctuations

An exposed membrane absorbs solar radiation during the day and its surface temperature rises. It re-radiates the absorbed heat at night and its surface temperature drops. Diurnal (daily) temperature fluctuations create thermal stresses in the membrane, affecting its long-term performance and its ability to protect a building from water infiltration. *Figure 6* shows the daily membrane temperature fluctuation (daily maximum temperature – daily minimum temperature) of the Reference Roof and the Green Roof and the daily ambient temperature fluctuations.

Observation Period	Median Daily Temperature Fluctuation (daily maximum temperature – daily minimum temperature		
	Reference Roof Membrane	Green Roof Membrane	Ambient
Winter 2001	9°C (16°F)	6°C (11°F)	10°C (18°F)
Spring 2001	46°C (83°F)	6°C (11°F)	13°C (23°F)
Summer 2001	47°C (84°F)	7°C (13°F)	12°C (22°F)
Fall 2001	23°C (41°F)	5°C (9°F)	8°C (14°F)
Winter 2002	9°C (16°F)	7°C (13°F)	9°C (16°F)
Spring 2002	42°C (76°F)	6°C (11°F)	10°C (18°F)
Summer 2002	47°C (84°F)	6°C (11°F)	12°C (22°F)

Table 2: Median daily temperature fluctuation of the roof membranes on FRF during the observation period (Nov 22, 2000 – Sep 30, 2002).

The Green Roof moderated the daily temperature fluctuations that the membrane experienced during early winter (November and December), while the membrane temperature of the Reference Roof followed the daily ambient temperature fluctuations. This protection was somewhat dissipated during the accumulation of snow, and once heavy snow coverage was established (January and February), both roofing membranes were protected from temperature fluctuations. The Green Roof significantly moderated the daily temperature fluctuations experienced by the roof membrane during the spring and the summer. The daily membrane temperature fluctuations of the Green Roof were consistently lower than the diurnal ambient temperature fluctuations. *Table 2* summarizes the daily temperature fluctuations in the roof membrane and the atmosphere over the observation period. The exposed membrane in the Reference Roof experienced high daily temperature fluctuation, with a median of 42-47°C (76-85°F). However, the Green Roof reduced the temperature fluctuation in the roof membrane throughout the year, keeping a median fluctuation of 5-7°C (9-11°F) only.

Energy Efficiency

The Green Roof was found to be effective in helping to keep the building cool in the summer. The plants and the growing medium in the Green Roof kept the roofing membrane cool by direct shading, evaporative cooling from the plants and the growing medium, additional insulation values from both the plants and the growing medium, and the thermal mass effects of the growing medium.

Heat flow through the building envelope creates energy demand for space conditioning in a building. *Figure 7* shows the heat flow through the roof on a summer day as measured by the three heat flux transducers embedded in each roof section. These transducers were calibrated such that positive heat flow represents heat

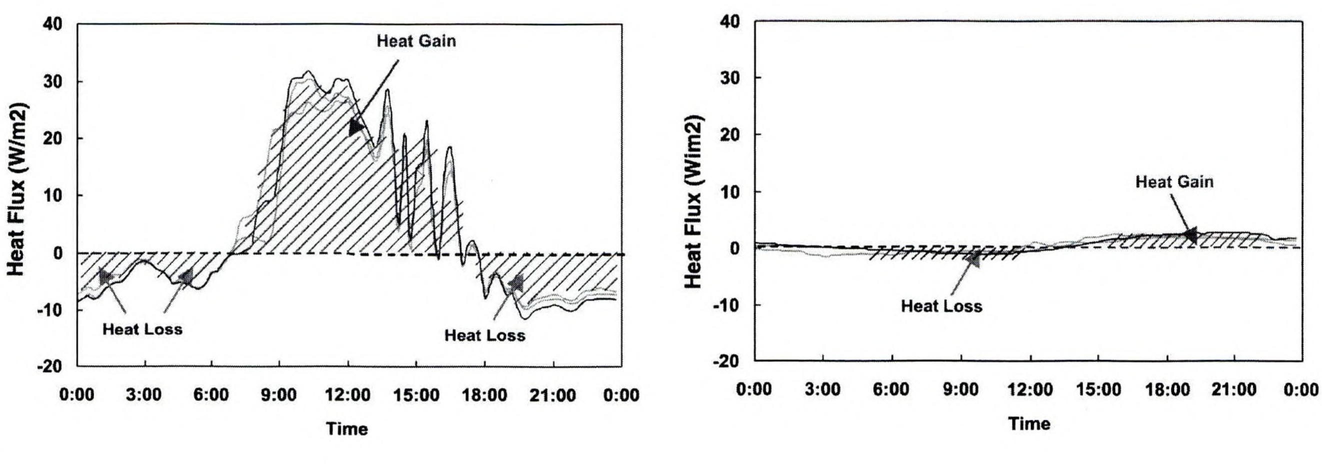

Figure 7: Heat flow through the roofing systems on a summer day (July 16, 2001) indicated that the Green Roof reduced the heat flow through the roofing system significantly.

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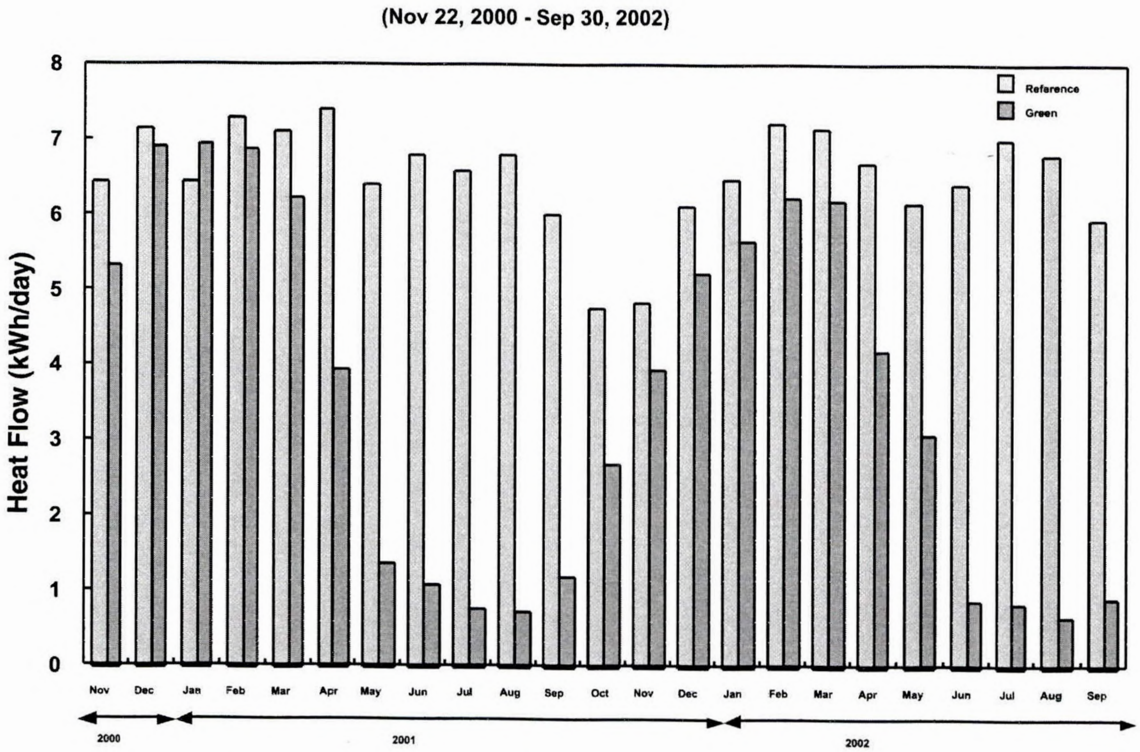

***Figure 8:** Heat flow measurement showed that the average daily energy demand due to the heat flow through the Green Roof was significantly less than that of the Reference Roof in the spring and summer.*

entering the roof at the installed location while negative heat flow means heat leaving the roof. The membrane on the Reference Roof, being exposed to the elements, absorbed solar radiation during the day and re-radiated the absorbed heat at night, creating positive heat flow in the afternoon and negative heat flow in the early morning and evening. The Green Roof significantly moderated the heat flow between the building and its surrounding through the roofing system. In the winter, data from the FRF showed that once the snow coverage was established, the heat flow through both the Reference Roof and the Green Roof became the same, as snow coverage provided good insulation and stabilized heat flow through the roof.

Figure 8 summarizes the average daily energy demand for space conditioning due to heat flow through the roof only. The energy efficiency of the Green Roof was slightly better than that of the Reference Roof in the fall and early winter, as the green roof system acted as an insulation layer. However, as the growing medium froze, its insulation value was greatly diminished. Snow coverage provided excellent insulation to the roofing system and stabilized the heat exchange between the building and its surrounding. The snow coverage on the roof was not uniform in early winter, due to the wind and the influence of the high parapet. Once snow coverage was established on the roof, heat flow through both roofs was almost the same.

The Green Roof significantly outperformed the Reference Roof in spring and summer (April to September). Solar radiation has a strong influence on the heat flow through the roof. The membrane on the Reference Roof, being exposed to the elements, absorbed solar radiation during the day and re-radiated the absorbed heat at night, creating high daily energy demand for space conditioning. On the other hand, the growing medium and the plants enhanced the thermal performance of the Green Roof by providing shading, insulation, and evaporative cooling. It also acted as a thermal mass, which effectively damped the thermal fluctuations going through the roofing system. The average daily energy demand for space conditioning due to the heat flow through the Reference Roof was 6.0-7.5 kWh/day (20,500-25,600 BTU/day), as shown in Figure 8. However, the growing medium and the plants of the green roof modified the heat flow and reduced the average daily energy demand to less than 1.5 kWh/day (5,100 BTU/day), a reduction of over 75%. Note that these values were due to the heat flow through the roof only (36 m^2 or 400 ft^2) and did not include heat flow through other parts of the building envelope.

The Green Roof was more effective in reducing heat gain in the spring/summer than heat loss in the fall/winter. This is because the green roof can reduce heat gain through shading, insulation, evapotranspiration, and thermal mass. However, it can reduce heat loss only through improved insulation and decreased radiation heat losses. This is effective on summer evenings, but not in winter, when the growing medium is frozen and the improved

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insulation and decreased radiation heat loss effects were dominated by snow coverage. *Table 3* shows the total heat flow through the roof surfaces of FRF normalized with the roof area from November 2000 to September 2002. During the 22-month observation period, the Green Roof reduced 95% of the heat gain and 26% of the heat loss as compared to the Reference Roof, with an overall heat flow reduction of 47%. Since an extensive green roof was more effective in reducing heat gain than heat loss, and Ottawa is in a predominantly heating region, it is expected that its effectiveness will be more significant in warmer regions.

	Reference Roof	Green Roof	Reduction
Heat Gain	19.3 kWh/m^2 (5900 BTU/fT^2)	0.9 kWh/m^2 (270 BTU/ft^2)	95%
Heat Loss	44.1 kWh/m^2 (13500 BTU/ft^2)	32.8 kWh/m^2 (10100 BTU/ft^2)	26%
Total Heat Flow	63.4 kWh/m^2 (19400 BTU/ft^2)	33.7kWh/m^2 (271 BTU/ft^2)	47%

Table 3: Normalized (per unit area) heat flow through the roof surfaces of FRF during the observation period (Nov 22, 2000 – Sep 30, 2002).

Stormwater Runoff

The Green Roof delayed stormwater runoff, reduced the peak runoff rate, and the runoff volume. The extent of the reduction depends on many factors, such as the rain intensity and duration and the wetting history of the growing medium (the moisture content of the growing medium before the rain event). For example, during a light rain of 19 mm (0.75 in.) in 6.5 h, the Green Roof delayed the runoff by 95 min (1.5 h) and the runoff volume was 2.9 mm (0.11 in.) – a reduction of 85% (*Figure 9a*). On the other hand, during a heavy rain of 21 mm (0.83 in.) in 21 min, the Green Roof delayed the runoff by four minutes only and the runoff volume was 5.7 mm (0.22 in.) – a reduction of 73% (*Figure 9b*).

Figure 10 shows the total rain and runoff measured at the FRF during spring and summer 2002. Note that the Green Roof was not as effective in June as in the other months. This was because it rained steadily during June, and so the growing medium did not have enough time to dry out between rainfall and was saturated with water. This reduced the runoff retention efficiency significantly.

In total, the Green Roof retained (and diverted through evaporation/evapotranspiration) 245 mm (9.64 in.) out of the 450 mm (17.72 in.) of rain that fell during April to September 2002 – a runoff reduction of 54%.

The Green Roof was an extensive system with grass growing in 150 mm (6 in.) of lightweight soil. It is expected that green roof systems could be designed with deeper and more adsorbent soil and more vegetation to deliver even higher stormwater retention performance.

CONCLUSIONS

Observation from the Field Roofing Facility showed that a generic extensive green roof with 150 mm (6 in.) of growing medium could reduce the temperature of the roof membrane significantly in the summer. The exposed roof membrane on the Reference Roof was recorded to reach over 70°C (158°F) in the summer but that under the Green Roof rarely reached over 30°C (86°F). Also, the Green Roof modified the temperature fluctuations that the roof membrane experienced, especially in the warmer months. The median daily temperature fluctuation of the membrane on the Reference Roof in spring

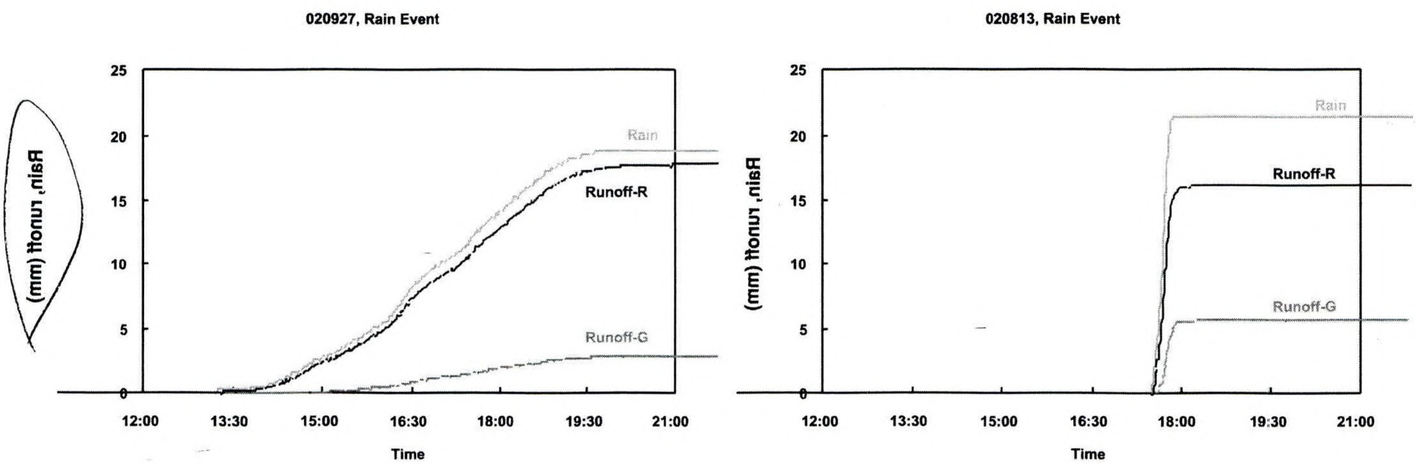

Figure 9: Hydrographs (cumulative rainfall plots) of two rain events of different intensity (a) light rain and (b) heavy rain.

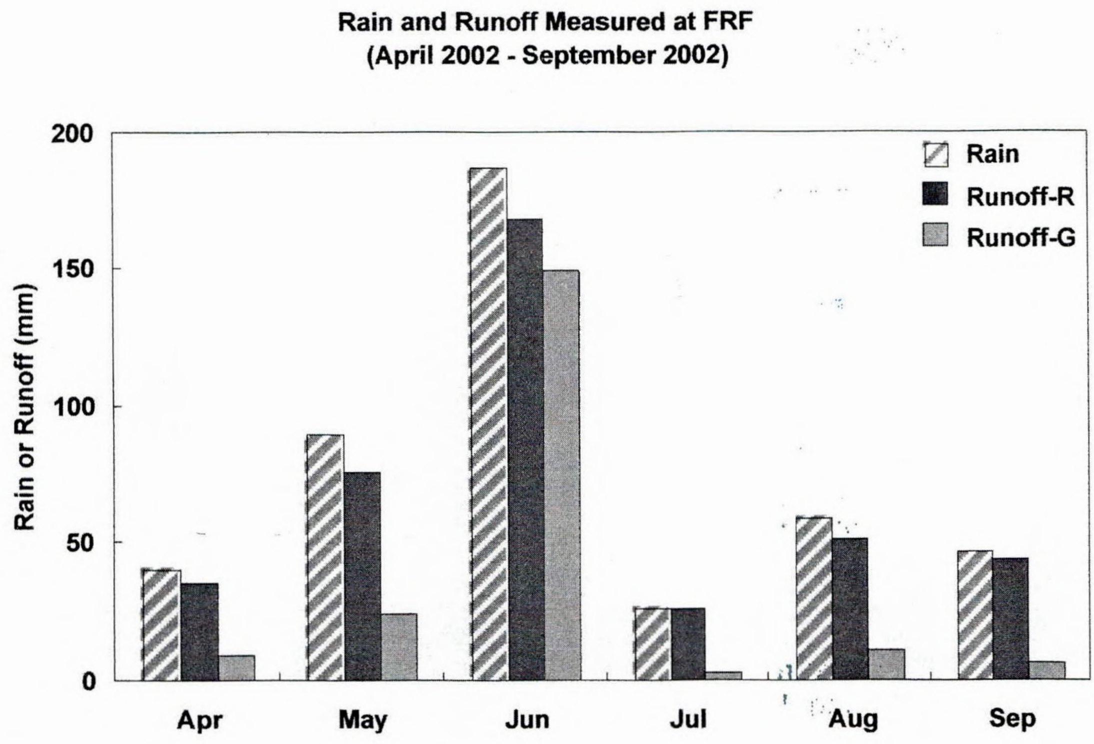

Figure 10: Rainfall and runoff measured at the FRF during April to September 2002.

and summer ranged from 42 to 47°C (76 to 85°F). However, the Green Roof reduced the temperature fluctuation to 5-7°C (9-11°F). The Green Roof also significantly moderated the heat flow through the roofing system in the warmer months. The average daily energy demand for space conditioning due to the heat flow through the roof was reduced from 6.0-7.5 kWh/day (20,500-25,600 BTU/day) to less than 1.5 kWh/day (5,100 BTU/day) as measured on the Reference Roof and the Green Roof, respectively. This corresponded to a reduction of over 75%. The Green Roof was shown to delay runoff and reduce peak runoff rate and volume. It retained 245 mm (9.64 in.) out of the 450 mm (17.72 in.) of rain that fell from April to September 2002 – a reduction of 54%.

IMPLICATIONS FROM THE STUDY

Analysis of the data that have been collected from the Field Roofing Facility suggests that an extensive green roof can lower the temperature and modify the temperature fluctuations that are experienced by roof membranes. The reduction in temperature reduces the effects of heat aging from natural exposure and the moderation in temperature fluctuations decreases the thermal stress on the membrane; both mechanisms can possibly extend the life of the roof membrane. The reduction in roof surface temperature can help to lower the urban heat island effects as well. Green roofs can moderate heat flow through the roof through shading, insulation, evapotranspiration, and thermal mass effects. This reduces the energy demand for space conditioning, most significantly in spring and summer. Green roofs can also delay runoff and reduce the peak runoff rate and runoff volume. This delay in peak flow and reduction in runoff volume suggest that green roofs can reduce the load on stormwater sewage infrastructure and help minimize the frequency of combined sewage overflow (CSO) events in urban area.

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